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13. ABSTRACT (Maximum 200 words)

   Two systems of the on-chip signal processing for handheld chemical agent sensors have been investigated. The principle of one on-chip signal processing is dependent on the resistance changes of the chemical sensor or chemical materials. The other principle is dependent on the impedance test. One prototype was built and delivered. The other three protoypes can be demonstrated. Two detection/amplification concepts were explored. The resolution of the relative resistance measurement is better than 10^{-6}. Suggestions for the future development are proposed.

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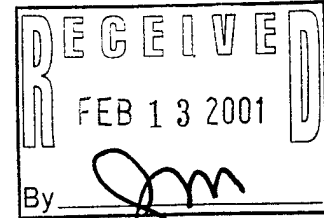## Prototype of On-Chip Signal Processing for Handheld Chemical Agent Sensors

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Abstract

Two systems of the on-chip signal processing for handheld chemical agent sensors have been investigated. The principle of one on-chip signal processing is dependent on the resistance changes of the chemical sensor or chemical materials. The other principle is dependent on the impedance test. One prototype was built and delivered. The other three prototypes can be demonstrated. Two detection/amplification concepts were explored. The resolution of the relative resistance measurement is better than 10^{-6}. Suggestions for the future development are proposed.

Primary Goals

The primary goals related to the study **of the Prototype of on-chip signal processing for handheld chemical agent sensors** are the following:

1. To investigate the detector/ amplifier techniques for chemical agent sensors.
2. To demonstrate the feasibility of the signal processing unit.
3. To design and build a prototype of the on-chip signal processing for handheld chemical agent sensors.
4. To test the signal processing prototype with the chemical agent sensors using conductive polymer developed at the Army Research Laboratory in Aberdeen, Maryland.
5. To deliver a prototype of the signal conditioning and amplifying device that is suitable for handheld applications for evaluation purposes.

Summary of accomplishment

1. Investigated two detection/amplification approaches. One of the on-chip signal processing approach is to detect the resistance changes of the chemical sensor. The other is to evaluate the impedance changes of the chemical sensors.
2. Demonstrated the on-chip signal processing concepts using the Lock-in Amplifier Model 128, fabricated by *EG&G* Company.
3. Designed and fabricated four prototypes of on-chip signal processing unit for handheld chemical agent sensors:
   (1) CST-2 Chemical Sensor Resistance Tester
   (2) CSIT-1 Chemical Sensor Impedance Tester
   (3) CST-1 AC Chemical Sensor Resistance Tester
   (4) Miniature Chemical Sensor Alarm
4. Tested three Prototypes (1) to (3) with the chemical agent sensors using conductive polymer developed at the Army Research Laboratory in Aberdeen, Maryland.
5. One prototype CST-2 Chemical Sensor Resistance Tester was delivered and the other three have been demonstrated. The resolution of the relative resistance measurement is better than 10^{-6}. The sizes are 3.25"x 4.38"x1.5"for the Prototypes (1) to (3), and 1.38"x 2.12"x 0.58" for Prototype (4).
6. More advanced signal processing methods have been suggested in anticipation in rapid improvement of the CMOS technology.

1. Introduction

The development of chemical agent sensors capable of discrimination of different analytes, toxins, and bacteria has become increasingly important for military, environmental, medicinal, food processing/evaluation, health and safety, remote sensing, and chemical processing applications. A recent advance in modern microelectronics is the ability of micro chemical laboratory and bio-sensors on a chip [1]. It has made many new applications in chemical and bio-sensors practical, such as hand-held devices for detecting different chemical agents in air and in water. There have been many studies of different sensing mechanisms including using conductive polymers for detecting gases [2], using a polymer-coated sensing thermopile to detect Enthalpy changes [3]. However, there is little effort in developing integrated signal processing discriminating systems on the same chip. Because the sensor signals in many micro sensors are extremely small, special signal processing circuits are needed to bring the signals out to provide useful information for the users. Increasing the measuring accuracy and decreasing noise is of paramount importance for the on-chip signal-processing unit. In our studies, we investigated two special detection/amplification techniques and built four prototypes. One prototype was delivered and the other three have been demonstrated. The resolution of the relative resistance measurement is better than 10^{-6}. Miniaturization promises to bring hand-held chemical agent sensors into many critical application fields. CMOS-technology offers the possibility to pack the sensor active part and signal processing electronics on one single chip. With the fast pace of the CMOS technology development, miniaturization for many elaborated systems will be possible. Suggestions have been made for future on-chip signal processing developments.

2. Basic Test Principles
(1) DC or AC Wheatstone Bridge method

Because characteristic changes of the polymer upon exposure to an analyte resulting in the resistance changes of the polymer film, this enables a direct low-power electrical signal readout to be used as the sensing signal. The resistance change is the resistance deviation δR. To measure the relative resistance deviation $\delta R/R$ of the polymer film before, during, and after exposure to various analytes, the well known DC or AC Wheatstone Bridge method is the most precise and the easiest way. By using the Wheatstone bridge a sensitive **resistive transducer** can be made. The basic principle of the Wheatstone Bridge method is shown in Fig. 1.
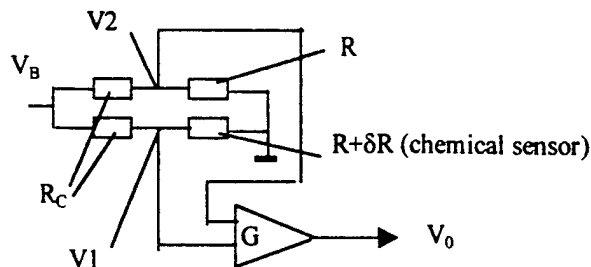

Fig. 1 Schematic of Wheatstone Bridge

The basic equations for calculation:

$$V_0 = G(V_2 - V_1) = GV_B \frac{\dfrac{R_c}{R}\dfrac{\delta R}{R}}{(\dfrac{R_c}{R}+1)(\dfrac{R_c}{R}+1+\dfrac{\delta R}{R})}$$

$$\frac{\delta R}{R} = \frac{-V_0(\alpha+1)^2}{GV_B\alpha - E_0(\alpha+1)}, \quad \alpha = \frac{R_c}{R}$$

V_B is the voltage of the source which can be DC voltage source or AC voltage source.

(2) AC Quasi-balanced Bridge method[4]

In addition to resistance changes, the absorption of analyte molecules into the chemically sensitive polymer layer (film) may lead to changes in its relative dielectric constant. This results in both resistance and capacitance changes or impedance change. By measuring the impedance changes, these will add new dimension in discriminating different analytes. The AC Quasi-balanced Bridge is an impedance measurement method. Using this method the resistance and capacitance of the test sensor can be analyzed. There are many different methods and techniques for measuring the impedance, such as the null (balance) type bridge which requires adjustments to measure the impedance, and the meter method which measures voltage and the current. Meters are faster and easier to use, but the bridge method is more accurate and has far more dynamic range. In this project we take advantage of the lock-in amplifier. An AC Quasi-balanced Bridge method is used. The basic principle of the AC Quasi-balance Bridge method is shown in Fig.2.

The Bridge consists of a resistance potentiometer Rp (a Sliding resistive Wire), an unknown Z (chemical sensor), and a known standard resistance Rst. The individual bridge elements are then Z, Rs, (1-x)Rp, and xRp. A sinusoidal voltage Vs with required frequency, ω, is applied to the bridge. Vd the potential difference between the point of the potentiometer and the node formed by the resistance Rs and the impedance Z, is taken as the output of the sensor.
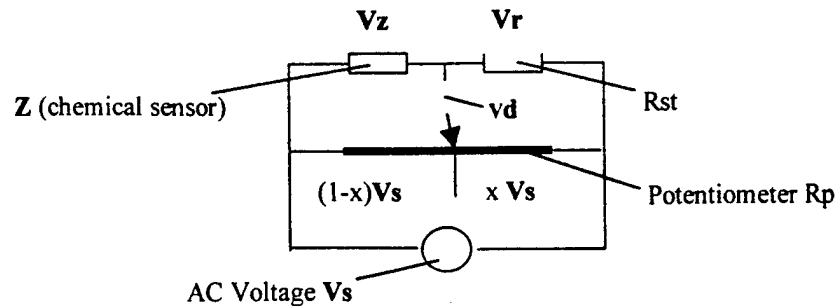
Fig.2 Schematic of the AC Quasi-balanced Bridge method

3

The two Quasi-balanced points are obtained on the bridge by varying the center position of the potentiometer. If the impedance to be measured is capacitive, the balance conditions are that the voltage **Vd** is in quadrature ($\phi=90°$) with the source voltage **Vs** and in quadrature with **Vz**, the voltage across impedance **Z**. The phase-sensitive detector (PSD) will indicate zero, when **Vd** is in quadrature with **Vz** and in quadrature with **Vs**. For the first quasi-balanced point, let the setting of the potentiometer x be m(i.e., **Vd** and **Vz** are in quadrature) and for the second, be n (i.e., **Vd** and **Vs** are in quadrature). When x=n. Let $Z=Rs+jXs=Rs+1/j\omega Cs$ in the series-equivalent representation of the impedance. **Rs** and **Xs** can be calculated by the following equations.

$$R_S = R_{St} \frac{m(1-n)(1-m)}{(1-n)m^2 + n - m}$$

$$X_S = -\frac{\sqrt{\dfrac{n-m}{1-n}}(1-n)(1-m)}{(1-n)m^2 + n - m}$$

If the impedance to be measured is a pure resistor R, the present scheme (shown in Fig.2) becomes a simple Wheatstone bridge with AC excitation. When the bridge is balance the **Vd** is reduced to zero. At this point x=m=n and

$$R = R_{St} \frac{1-m}{m}$$

3. Detection/Amplification on-chip

Because the signal to noise ratio of the low-level signal produced by the resistance bridge circuit or the impedance bridge circuit is small, the on-chip signal processing with signal amplification is the core technique in our studies. We introduced two special detection/amplification methods.

(1) On-chip low-noise differential instrumentation amplifier[5]

To measure relative resistance deviation, we must convert $\delta R/R$ to voltage V_0. The instrumentation amplifier (IA) is an on-chip differential amplification device with very high input impedance, shown in Fig.3. The signals of the resistance bridge were amplified by the differential amplifier while the common-mode disturbance was canceled. Thus the difference amplifier provides the ability to reject common-mode signal components (such as noise or undesired DC offsets) while amplifying the differential-mode components. We use the two op-amp buffers to provide impedance isolation between bridge transducers, while to increase the input impedance of the differential amp.
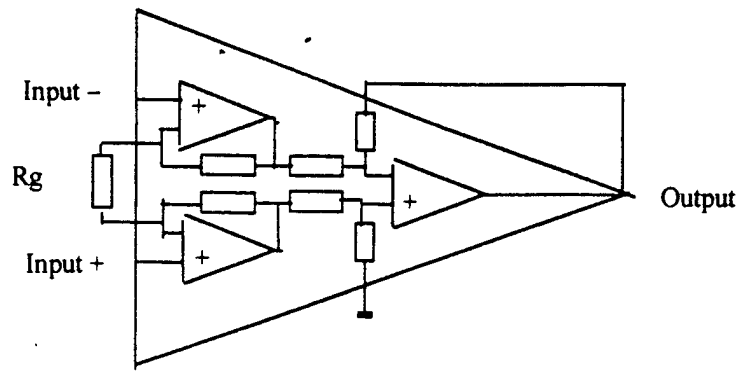
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Fig. 3 Block diagram representation of IA.

(2) On-chip Difference Amplifier and Lock-in Amplifier[6]

The combination of the difference amplifier and lock-in amplifier is suitable for conversion of $\delta R/R$ to voltage V_0 in the AC bridge, shown in Fig.4.
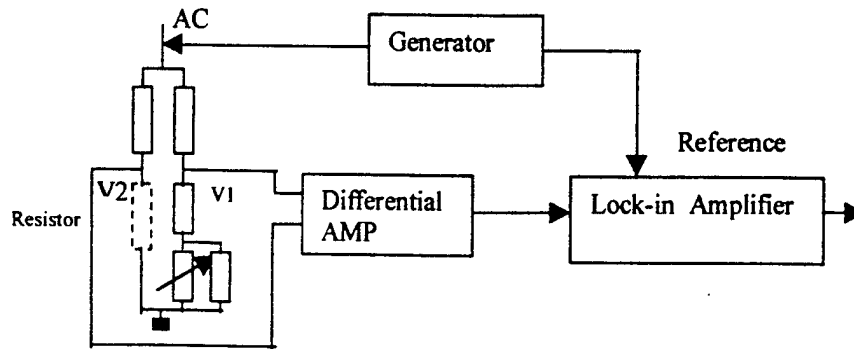

Fig. 4 AC bridge with difference amplifier and lock-in amplifier

The low-level signals amplified by differential amplifier will still have the low frequency noise components, such as temperature-dependent drift. Lock-in amplifiers are able to measure signals accompanied by relatively high levels of noise and interference. The principle of the lock-in amplifier is shown in Fig. 5.
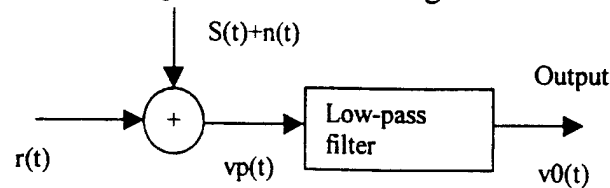

Fig.5 Lock-in amplifier with synchronous phase sensitive detected.

$$v_p(t) = r(t)[s(t) + n(t)]$$

where s(t) is the signal to be measured, r(t), reference signal, and n(t) represents the entire disturbance due to additive noise and interference.

Assume:

$$s(t) = \sqrt{2}V_S \cos[\omega_S t + \phi_S]$$

$$r(t) = \sqrt{2}V_R \cos[\omega_R t + \phi_R]$$

$$V_P(t) = V_S V_R \cos[(\omega_S + \omega_R)t + \phi_S + \phi_R] + V_S V_R \cos[(\omega_S - \omega_R)t + \phi_S - \phi_R]$$

If $\omega_S = \omega_R$, $\phi = \phi_S - \phi_R$, the output of the low-pass filter is the phase sensitive response in a form of DC:

$$V_O = K V_S V_R \cos[\phi]$$

It is clearly that the asynchronous signals such as noise and interference components give rise to an alternating response in the form of "beat" frequency product. The rejection of a large part of the background noise spectrum is inherent in the operation of a synchronous detector and that the frequency selectivity of the detector is governed by the properties of the low-pass filter.

$$\frac{SNR_O}{SNR_I} = \frac{B_I}{B_O}$$

where, B_I is the bandwidth of white noise, and B_O is the bandwidth of the low-pass filter. SNR_O and SNR_I are the signal to noise ratio of output and input, respectively.

For the synchronous type, if v_S and v_R in quadrature($\phi = 90°$) $V_O = 0$.

4. Construction of Prototypes

For this short-term and low budget project we took advantages of the commercial on-chip amplifiers to build the prototypes.

(1) CST-2 Resistive Chemical Sensor (delivered)

INA114 Precision Instrumentation Amplifier, product of Burr-Brown Inc., is used as the on-chip signal processing. The scheme is shown in Fig.6
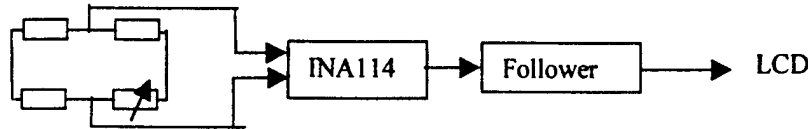

Fig.6 Scheme of CST-2

(2) CSIT-1 Impedance Chemical Sensor

The combination of the difference amplifier OP2227 and the lock-in amplifier AD630 is used as the on-chip detection/amplification unit and as the readout circuit of the potentiometer n and m values. The scheme is in Fig. 7.
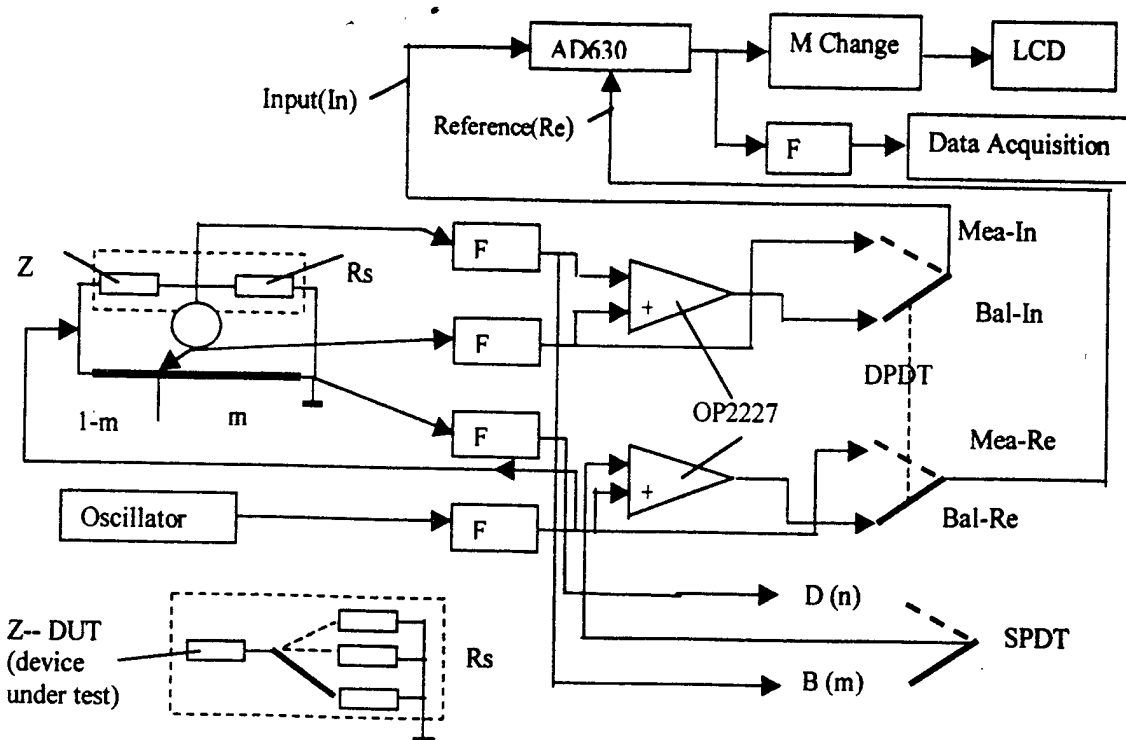
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Fig. 7 Scheme of CSIT-1

(3) CST-1 AC Resistive Chemical Sensor

The combination of the difference amplifier OP2227 and the lock-in amplifier AD630 is used as the on-chip detection/amplification unit. The output of the amplifier is input to the Data acquisition board CIO-DAS 1601/12. The tested results can be directly input into Excel program package by download DAS-wizard software. The data analysis and graphic can be performed. The scheme is shown in Fig. 8.
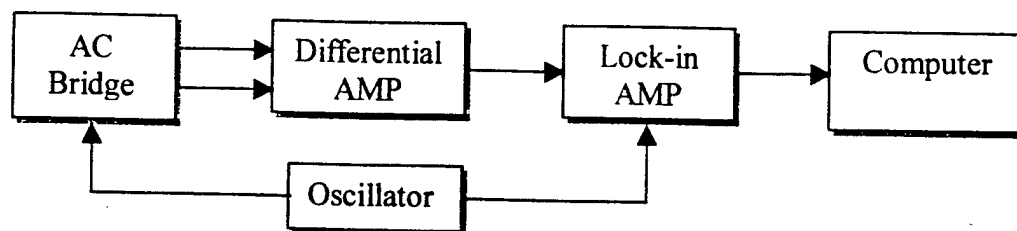

Fig. 8 Scheme of CST-1

(4) Miniature Chemical Sensor Alarm

A minimazed prototype with DC bridge is assembled using the single supply ICs as on-chip signal processing unit. The combination of the single supply instrumentation amplifier INA122 & comparator TLC372 is show in Fig. 9. It is in a 2"x 1"box with battery.
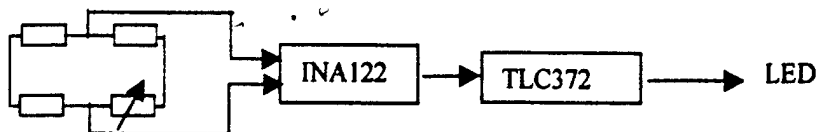
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Fig. 9 Scheme of Chemical Sensor Alarm

5. Future work

Three on-chip processing systems for hand-held chemical agent sensors are suggested.

(1) Chemical agent sensor array with resistance network test system. This system can be developed as an "electronic nose" or "electronic tongue".

(2) Embedded Micro-controller controlled chemical agent sensor system.

(3) Wireless chemical agent sensor system.

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